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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this work is to develop techniques to overcome the fundamental limits of present frequency standards--the second and residual first-order Doppler shifts. To this end we study suitable frequency reference transitions in ions which are stored on electromagnetic traps and cooled by radiation pressure to < 1K.

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Summary of Work on

"COOLED ION FREQUENCY STANDARD"

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National Bureau of Standards
Boulder, Colorado 80303
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Contract Description

The purpose of this work is to develop techniques to overcome the fundamental limits of present methods for high resolution spectroscopy and frequency standards--the second and residual first-order Doppler shifts. To this end, we study suitable frequency reference transitions in ions which are stored in electromagnetic traps and cooled by radiation pressure to < 1K.

Scientific Problem

The scientific problems are (1) to suppress second order and residual first order Doppler shifts in atomic frequency standards in a fundamental way--by substantially reducing the kinetic energy of ions stored ion electro-magnetic traps, (2) to study suitable reference transitions in ions that can be used as frequency standards, and (3) to study the problems generic to all stored ion frequency standards. The goal is to achieve at least a factor of 100 improvement in accuracy over the present best device, the Cesium beam frequency standard, which has an accuracy of approximately one part in 10^{13}.

Scientific and Technical Approach

Laser cooling is employed on all experiments in order to suppress Doppler shifts. Temperatures < 0.1K are routinely achieved. To avoid light shifts on "clock" transitions we investigate "sympathetic cooling" where one ion species is laser cooled and by Coulomb collisions cools another ion species of spectroscopic interest. We will continue experiments on Mg^+ and Be^+ in order to study generic problems with traps. We are developing a separate experiment for Hg^+ ions. These experiments have the goal of realizing a frequency standard with 10^{-15} or better accuracy.

PROGRESS DURING LAST CONTRACT PERIOD

A. EXPERIMENTAL

1. Sympathetic cooling.

For the experiments on rf and microwave spectroscopy, especially for an ion microwave frequency standard, we think a significant advance can be made by use of a process called sympathetic cooling. In sympathetic cooling, two ion species are stored in the trap simultaneously. (Say $^9Be^+$ and $^{201}Hg^+$). One species which is easily laser cooled ($^9Be^+$, because of the high laser powers easily generated) sympathetically cools the other ion species via Coulomb collisions. This technique has two important advantages over the direct laser cooling method (employed in our first $^9Be^+$ clock experiment): (1) Laser cooling can be supplied by a laser which is easy to make -- like the one for Be^+. In the Hg^+ experiments we have determined that it will be very difficult to obtain much more 194 nm power for direct cooling -- the main limit is imperfections in the nonlinear crystals which causes thermal "blooming" of the beams. (2) Since the cooling laser will in general be non resonant with the energy levels of the "clock" ion, a.c. stark shifts from the cooling laser can be negligible ($<<10^{-15}$). Therefore, the cooling laser can be left on continuously and the reheating encountered in the direct laser cooling experiments can be avoided. In addition, interrogation times of clock transitions can be made much longer -- linewidths of less than 1 millihertz do not seem unreasonable (interrogation times of greater than 500 s). Moreover, the temperature of the ions and therefore the second order Doppler shift will be much smaller and much more stable in this steady state situation and resulting frequency shifts should be easier to characterize than in the transient condition of the $^9Be^+$ clock.

We have recently realized this technique using $^9Be^+$ and $^{198}Hg^+$ ions. The results are that the basic technique is valid; by laser cooling $^9Be^+$ ions, the $^{198}Hg^+$ ions were cooled to a temperature less than 1K. In addition, the shapes of the resulting two species plasma were measured and found to compare fairly well with theory. One interesting aspect of such plasma is that the

two species separate due to the differences in centrifugal forces as indicated
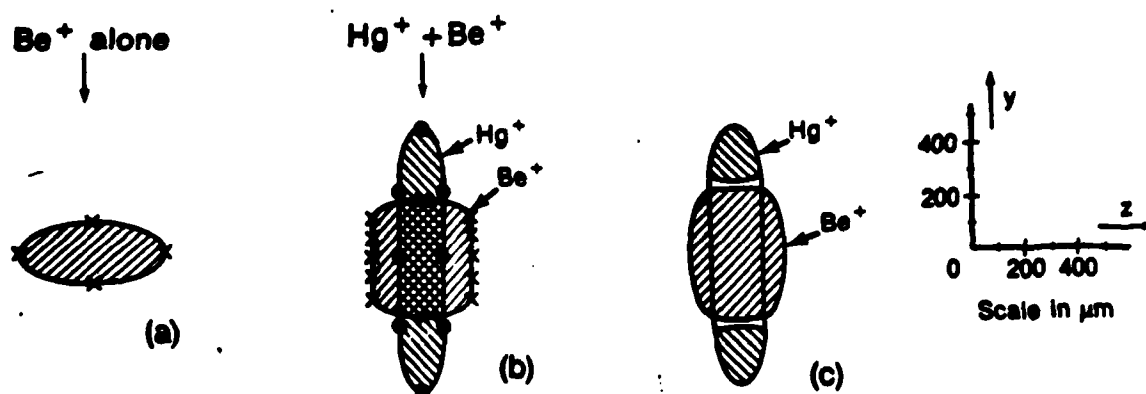in Figure 1.

Fig. 1. Experimental and theoretical shapes of ion plasmas. (a): $^9Be^+$ ion
plasma alone. (b): Same $^9Be^+$ ions as in (a), but with $^{198}Hg^+$ ions added.
(c): Theoretical shape generated for the same experimental conditions as in
(b).

2. Single $^{198}Hg^+$ ion laser cooling.

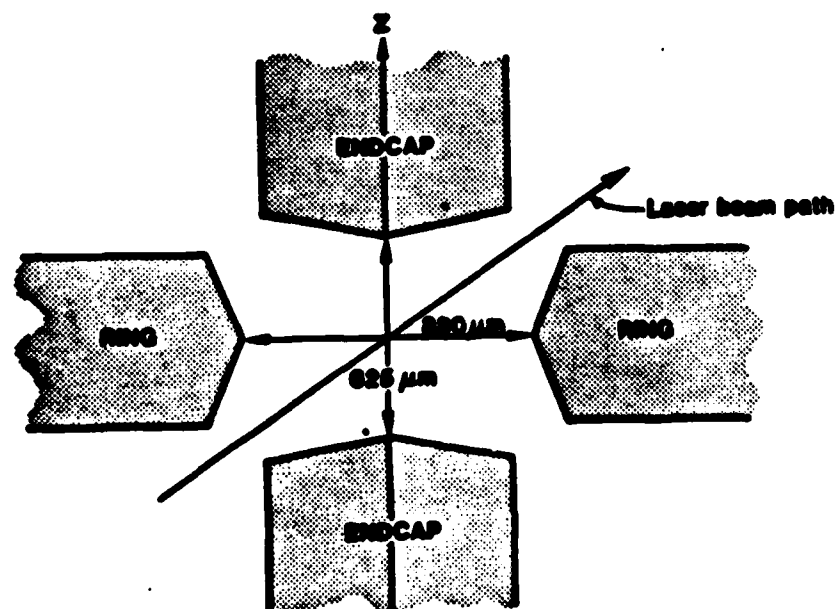We have stored single $^{198}Hg^+$ ions in the rf trap shown in Fig. 2.

Fig. 2. Schematic drawing showing cross section view of rf trap electrodes
for $^{198}Hg^+$. The electrodes are figures of revolution about the z-axis and are
made from molybdenum.

Typical operating conditions were an oscillating voltage of about 500 V applied between ring and endcaps at 20 MHz and a static potential of about 10 V between ring and endcaps in order to give an overall approximately spherical well. The 194 nm fluorescence light (see Fig. 3) scattered from the ion was imaged onto a plate about 20 cm away from the trap.
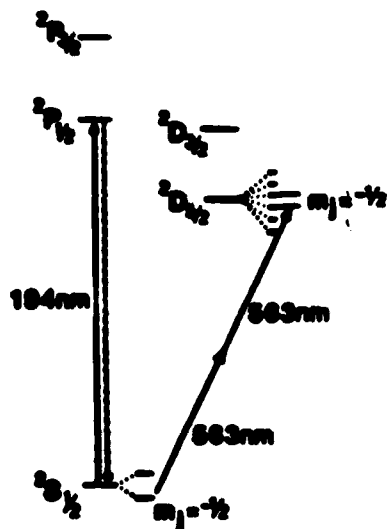

Fig. 3. $^{198}Hg^+$ level structure showing the 194 nm cooling transition and the $^2D_{5/2}$ level which can be excited via the 2 photon transition or a single photon quadrupole transition.

This plate had a 50 μm diameter aperture at the position of the ion's image so that the fluorescence from the ion could pass through the plate and be captured by a PMT. This technique avoided the background fluorescence from stray scattered light to a high degree. If the cooling laser frequency was swept from low to high values while observing the fluorescence light, curves like those in Fig. 4 resulted.

The radiation from the 194 nm cooling laser had a power of about 4 μW focused to a waist $\omega_0 \approx 10$ μm at the position of the ion. The curve is asymmetric as expected. This is because when the laser is tuned below the ion's resonant frequency, cooling takes place and the ion is well localized and has minimal Doppler broadening, therefore the scatter rate is high. As soon as the laser is tuned beyond the ion's resonant frequency, the ion rapidly heats causing an abrupt decrease in fluorescence because the laser beam/ion spatial overlap is

reduced and the Doppler broadening becomes significant. Hence, to a good approximation, we see only the low frequency side of the ion resonance.
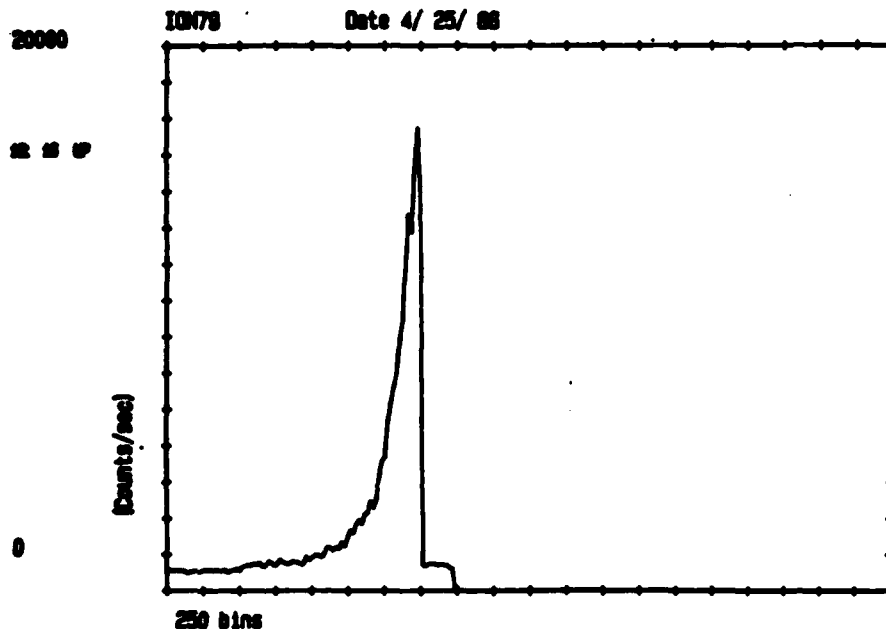

Fig. 4. Photon fluorescent counts (vertical axis) vs. 194 nm laser tuning (horizontal axis) for a single ^{198}Hg$^+$ ion.

We have also observed the 2 photon S → D transition on a single, cold ion. (Last year we observed this on a cloud of room temperature ions). Effort is currently underway to observe the S → D transition via quadrupole excitation; this would remove the a.c. Stark shift inherent in the 2 photon excitation. Work is also underway to investigate this transition as a possible optical frequency standard since the lifetime of the D state (0.1 s) gives an intrinsic Q of 10^{15}! Moreover, we expect to be able to reduce all systematic effects (including the second order Doppler shift) below 1 part in 10^{18}.

3. Ion Plasma Studies. (Penning Trap)

   a. Ion "Cloud" dynamics. The importance of this problem for high resolution spectroscopy is that the primary systematic error for a cloud of ions is expected to be the uncertainty in second order Doppler shift due to the rotation of the ion cloud. Therefore a detailed analysis of this motion is necessary to account for this effect. (We can usually cool the cyclotron and axial velocities to negligible values.) For our one species ion plasmas,

we are usually in the regime where the Debye length of the plasma is small
compared to its dimensions; in this case, for ions in thermal equilibrium, we
expect a "cloud" of constant density and no shear in the rotation velocity.
(If there is shear, frictional heating would occur which would tend to drive
the cloud to thermal equilibrium). We can search for shear by measuring the
rotational velocity induced first order Doppler shift of an optical transition
as a function of laser beam position perpendicular to the rotation (B field)
axis. This is shown in Figure 5; to the extent that the slope of the plot is
a straight line, there is no shear in the cloud. To within measurement
precision, this is the case.

Probe Beam Transverse Position (μm)
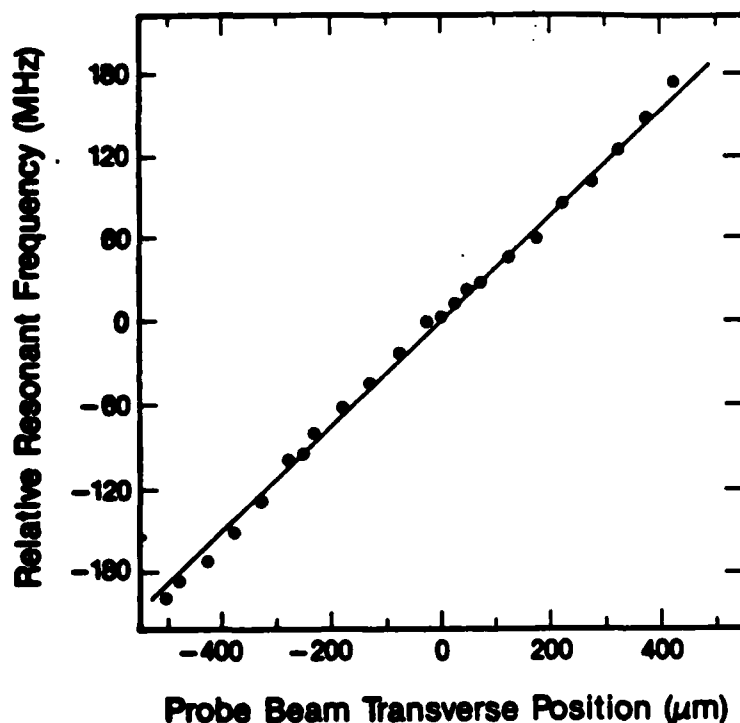
Fig. 5. Measured resonance frequency in Be$^+$ as a function of the transverse
position (perpendicular to the trap axis) of the probe laser beam. These
measurements, done with Hg$^+$ ions present in the trap, placed a limit on the
amount of shear in the Be$^+$ cloud. The statistical error in the data points is
smaller than the size of the points.

An additional result of our theory would indicate that the ion clouds are
uniformly charged spheroids of revolution (about the z or B field axis) and
that there is a definite relationship between the aspect ratio of the plasma
and the rotation frequency, independent of how the ion cloud is formed (by

laser cooling). Measurements are currently underway to test this theory and so far, agreement is good within our measurement precision of about 10%.

   b. Laser induced plasma oscillations. In most of our experiments on laser cooling with Penning traps, the laser simultaneously cools the cyclotron motion and compresses the ion cloud (reduces the magnetron radii). For certain conditions of laser detuning and spatial position, instabilities in the plasma occurs as indicated in the oscillatory fluorescence rate vs. time as indicated in Figure 6. We have observed similar behavior in all the
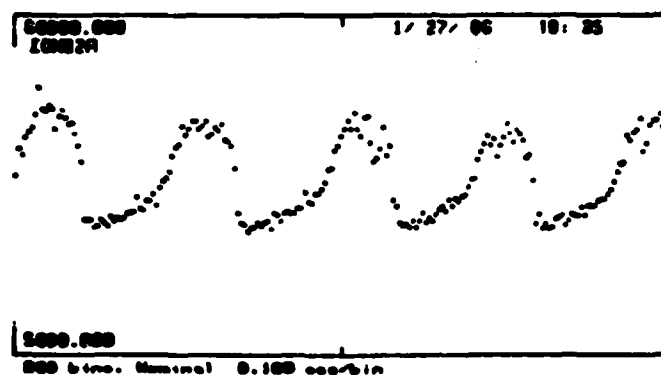

Fig. 6 Oscillatory fluorescence level vs. time from a cloud of $^9Be^+$ ions.

ion clouds stored in Penning traps. Clearly, in any high resolution optical pumping/double resonance experiment, this is a situation to be avoided since the signal would appear noisy. In the past we have used operating conditions away from such obvious instabilities but more recently we have discovered that even when the regular oscillations are absent, the fluorescence spectrum has 1/f noise below about 5 to 10 Hz. Therefore, although not as severe, this 1/f noise will limit the signal to noise in resonance experiments and therefore we must investigate this problem further. (See theory section).

   c. Liquid and solid plasmas. As an extension of previous work by us, we have reached higher values of Γ in our single species plasmas. Γ is a parameter which is approximately equal to the ratio of the Coulomb energy between nearest neighbor ions to the kinetic energy per ion. Specifically, $\Gamma = q^2/ak_BT$ where q = ion charge, k_B = Boltzmann's constant, T = temperature and a = mean spacing between ions, ie. $4\pi a^3/3 = n_0$, where n_0 is the ion density. For $\Gamma \approx 2$ the plasmas should show liquid properties; for $\Gamma \approx 150$ they should

become solids. Previously we had observed Γ=10, recently <u>we have observed</u> <u>Γ=100</u> (Determined by measuring density and temperature). These higher values of Γ were realized by using a "diagonal" cooling beam (one which entered and exited the trap in the gaps between ring and endcaps). In the future we hope to observe liquid and solid properties via Bragg scattering (see below).

4. <u>Apparatus construction</u>. Two new trap systems are nearing completion--one for the superconducting magnet (described in the next paragraph) and one for a special $^{24}Mg^+$ atom state switching experiment described in the proposed work.

B. THEORETICAL

1. <u>Trap design</u>. The special purpose computer program for trap design has been used on the rf trap (Fig. 2) and on two new traps. The most sophisticated one to date is shown in figure 7. By adjusting the aspect ratios and dimensions of the cuts in the traps, the fourth and sixth order terms in the potential are nulled (to within machining errors) which makes the motional resonant frequencies harmonic. A first paper on this computer solution has been accepted by Physical Review and a paper applying this in various cases is being prepared. This is useful for performing mass spectroscopy and more importantly for driving unwanted ions from the trap. For the trap of Fig. 7, the main emphasis is on axial symmetry. At this point, we think that all the unresolved problems in our ion clouds: limit on density, heating, and instabilities are caused by spurious angular momentum being coupled into the ions from the outside. Since we have shown that the effect of background gas collisions is negligible, we are fairly sure this angular momentum is coupled via trap asymmetries. Therefore particular attention has been paid to making the trap highly axially symmetric. This required not only precise machining and alignment but also the need for a second loading trap. During loading, some neutral Mg or Be will inadvertently be plated onto the trap inner electrode surfaces in an asymmetric way. The contact potential variations due to this plating (up to about a volt) would be prohibitively large in the experimental trap necessitating two separate traps.
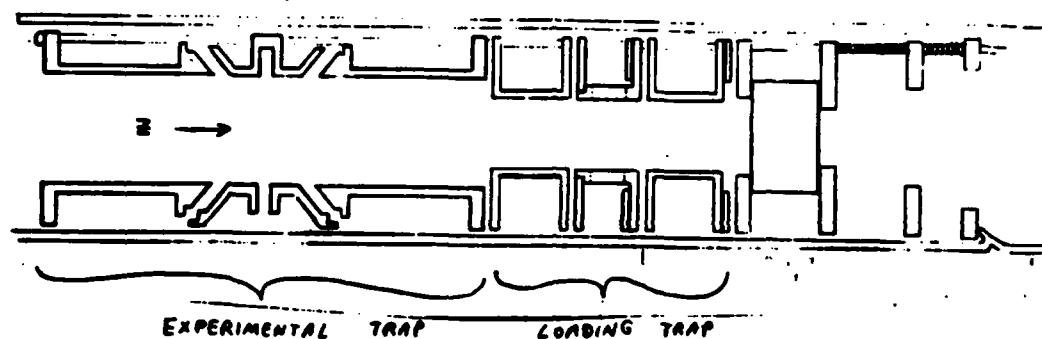
Fig. 7. New trap for superconducting magnet for ^{26}Mg$^+$, ^{25}Mg$^+$, and ^{9}Be$^+$ ions). The structure on the right is a second trap--for loading only.

2. **Laser Cooling.** Our previous papers on the theory of laser cooling in both harmonic and Penning traps have basically been single particle theories in that Coulomb repulsion between the ions was neglected. In the rf trap, including the Coulomb repulsion gives no substantial difference from the single particle laser cooling theory but for the Penning trap the situation is more complicated. This is primarily because to cool the axial and cyclotron degrees of freedom we must extract energy (this is the usual case) but to "cool" the magnetron degree of freedom (ie. reduce the magnetron velocity), we must add energy since most of the energy in this degree of freedom is potential energy. It is not surprising that trouble can occur in the special situation where we want to heat and cool at the same time. Recently, we have developed the theory for steady state (assuming a nonlinear angular momentum input which we think is due to trap asymmetries) and have just initiated measurements which seem to confirm this theory. Efforts are continuing to theoretically solve the dynamical problem and explain the oscillation behavior (Fig. 6). This theory is much more complicated and highly nonlinear since the laser cooling rate, torque input from the laser, cloud angular momentum, cloud density, shape, and size and the axial temperature and the cyclotron temperature are all nonlinearly interrelated. It is tempting to conjecture

that the periodic oscillations (Fig. 6) give rise to the 1/f noise through
deterministic chaos but not enough is known yet about the oscillation.

3. __Sympathetic cooling__. Self consistent computer solutions have been
generated for the two species ion plasma. One solution is shown in Figure 1.
Other cases are being investigated, for example the case of simultaneous
__antiproton/electron storage__. This case is particularly interesting in light
of the number of people trying to cool, accumulate and store antiprotons for
various experiments. Common to all of the groups is the idea to use electrons
to sympathetically cool the antiprotons in a Penning trap.

4. __Nuclear diamagnetism via shifts to atomic hyperfine structure__. A
strong magnetic field can distort both the electron cloud and the nucleus of
an atom, giving rise to small energy shifts in addition to those predicted by
the Breit-Rabi formula. Larson suggested that the very small frequency shift
due to nuclear distortion (nuclear diamagnetism) may be measurable in an
atomic system. We have calculated the size of this effect on the $|\Delta m_I|-1$
ground state frequencies of several atoms and ions. We find that in general
this shift is anomalously large (>50 mHz at 60 KG) in $^{201}Hg^+$. A shift of this
size would be easily observable. Shifts in $^{25}Mg^+$ are considerably smaller
(almost 3 orders of magnitude) but we anticipate being able to measure these
shifts to about 10% precision.

5. __Telegraphic atomic fluorescence__. Efforts are currently underway to
observe "telegraphic atomic fluorescence" in a three level system (in our case
the single Hg^+ ion). This experimental possibility was originally discussed
by Cook and Kimble and has been the subject of several other theoretical
papers in the last year (see below, in proposed work). We have recently
worked out the theory for observing telegraphic fluorescence via spontaneous
Raman scattering (a six level system).

Cook and Kimble discussed the statistics of fluorescence emitted by a single
three level atom (ground state "0", excited states "1" and "2"). Fluorescence
from the 0→1 "strong" transition reveals the discrete nature of the 0→2 "weak"
excitation (level 2 is assumed to radiatively decay slowly back to level 0).

In an alternative system, which is governed by the same rate equations as in Cook and Kimble's analysis, and should display the same fluorescence statistics, level 2 is excited from and "decays" back to level 0 via spontaneous Raman scattering. Consider a $^{24}Mg^+$ ion in a magnetic field (B>1 kG)[2]. Here "0" = $(3s^2S_{\frac{1}{2}}, M_J=-1/2)$, "1" = $(3p^2P_{\frac{3}{2}}, M_J=-3/2)$ and "2" = $(3s^2S_{\frac{1}{2}}, M_J=1/2)$. This system has the advantage that for a laser tuned near the $0\rightarrow1$ transition frequency, the ratio of the mean fluorescence "on" to "off" times is nearly independent of laser power and frequency fluctuations. This has been verified by examining the density matrix equations for the 6 level problem both analytically and on a computer.

6. **Temperature measurements via Raman scattering.** The present lower limit on temperature is limited by our ability to measure Doppler broadening on the linewidth of the strongly allowed first resonance transitions. For temperatures below 10 mK, the Doppler broadening is a small fraction of the natural width. This problem might be alleviated by driving a stimulated Raman transition between two nearly degenerate levels in the electronic ground state of the ions. In $^{24}Mg^+$, for example, the $^2S_{\frac{1}{2}}(M_J = -1/2) \rightarrow {}^2P_{\frac{1}{2}}(M_J = -1/2) \rightarrow {}^2S_{\frac{1}{2}}(M_J = +1/2)$ transition could be driven by using two laser beams separated by the $M_J = -1/2$ and $M_J = +1/2$ ground-state frequency difference. The effects of the laser linewidth would be suppressed by generating the two laser lines with a phase modulator (technique used by S. Ezekiel, MIT); the linewidth of the overall transition would be limited by the ground-state lifetime and thus could be extremely narrow. The intensity of the motional sidebands would depend on $\vec{v} \cdot (\vec{k}_1 - \vec{k}_2)$, where $\vec{k}_1$ and $\vec{k}_2$ are the wave vectors of the two laser beams and $\vec{v}$ is the ion velocity. Thus the angle between the beams could be chosen to optimize the temperature information.

We have theoretically modeled this problem for $^9Be^+$ ions. In this case the Raman transition would be between two ground state hyperfine sublevels. An experiment was initiated to observe this effect but has been postponed due to the early departure of the post-doc working on this project.

7. **Atomic clock theory.** We have tried to do a careful design study for an atomic clock based on our present state of knowledge of the system of ions stored in a Penning trap. This study, which will be published in the

proceedings of the Conference on Precision Electromagnetic Measurements (CPEM, June, '86), includes a detailed comparison of microwave clocks based on $^{201}Hg^+$, $^{25}Mg^+$, and $^9Be^+$. The main result of this study is that we think it would be advantageous to make the next step toward a rf/microwave clock by making one based on $^{25}Mg^+$ (or $^9Be^+$) rather than $^{201}Hg^+$ as we had originally planned. As discussed previously, the single reason for using $^{201}Hg^+$ vs. $^{25}Mg^+$ or $^9Be^+$ is that the "clock" hyperfine transition frequency is about 100 times higher than in Mg^+ or Be^+. All other things being equal--eg. linewidth and signal to noise ratio, the Q of the Hg^+ clock would be 100 times higher and the stability (not necessarily the accuracy) would be 100 times better.

With the main criterion being 10^{-15} accuracy, we have determined that the S/N is substantially less in the Hg^+ case and therefore we do not get the factor of 100 in stability. More realistically, a factor of 20 is possible. In addition, with the available 194 nm optical pumping power (about 5 μW limited by imperfections of available crystals) the optical pumping times are prohibitively long (perhaps an hour) making this system much more difficult to work with. (We could of course make a 194 nm build up cavity but this increases the complexity). There are several other practical factors including pressure problems with neutral Hg and the necessity to mix the hyperfine ground states (6 microwave oscillators required) which make the Hg^+ system much more difficult to work with.

Moreover, with sympathetic cooling, the performance of a Be^+ or Mg^+ clock would be substantially better than originally expected (primarily because of the expected narrower linewidths). We anticipate that the short term stability would be limited by available local oscillators (active hydrogen masers) when using Mg^+ or Be^+, so that the potential improvement available with Hg^+ could not be realized anyway (at the present time). This, coupled with the fact that the lasers, vacuum equipment and ancillary equipment are much easier to deal with in Mg^+ or Be^+ compel us to make our next clock experiment based on Mg^+ or Be^+. Ultimately, it still appears that the Hg^+ system would give better performance, but for the near future we can learn more about this system (Hg^+) by studying Mg^+ or Be^+.

8. <u>Synchrotron frequency divider</u>. If we are successful in the
development of an optical frequency standard, its use will be somewhat limited
since at present, devices do not exist to measure these frequencies in a phase
coherent way, ie; count cycles of the radiation. The techniques of harmonic
mixing (originally developed in the low frequency region) appear technically
feasible but so far have not been applied to the visible spectrum. Moreover,
such schemes are very cumbersome due to the many lasers and mixing stages
required. Additionally, the tuning range is limited.

The synchrotron divider could potentially overcome these difficulties. Aside
from its possible practical applications, many interesting basic phenonema
could be studied including the relativistic anharmonic oscillator, and extreme
nonlinear interactions in a new regime. Presently, we are studying some of
the basic processes involved. A graduate student is currently investigating
the possibility of using positive feedback to stabilize the magnetron orbit of
the electron.

OFFICE OF NAVAL RESEARCH

PUBLICATIONS[t] / PATENTS / PRESENTATIONS / HONORS REPORT

for

1 October 1985 through 30 September 1986

for

"COOLED ION FREQUENCY STANDARD"

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PAPERS SUBMITTED TO REFEREED JOURNALS
(Not Yet Published)

1. "Frequency Standards Based on Stored Ions", D.J. Wineland, Wayne M. Itano, J.C. Bergquist, and J. J. Bollinger, Proc. of the Conf. on Precision Electromagnetic Measurements (CPEM '86). To be submitted to IEEE, Trans. on Instrumentation and Measurement.

2. "Observation of Quantum Jumps in a Single Atom," J. C. Bergquist, R.G. Hulet, W.M. Itano and D.J. Wineland, submitted to Phys. Rev. Lett.

3. "A High Γ Strongly Coupled Non-Neutral Ion Plasma," L.R. Brewer, J.D. Prestage, J.J. Bollinger, W.M. Itano, and D.J. Wineland, submitted to Strongly Coupled Plasma Physics (NATO ASI Series) Eds: Forest J. Rogers, Hugh E. DeWitt.

4. "Simple Electrodes for Quadrupole Ion Traps," E.C. Beaty, submitted to J. Appl. Phys.

PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Energy and Radiative Lifetime of the $5d^9 6s^2$ $^2D_{5/2}$ State in HgII by Doppler-Free Two Photon Laser Spectroscopy," J.C. Bergquist, D.J. Wineland, Wayne M. Itano, H. Hemmati, H.-U. Daniel, and G. Leuchs, Phys. Rev. Lett. $\underline{55}$, 1567 (1985).

2. "Measurements of the g_J-Factors of the $6s$ $^2S_{1/2}$ and $6p$ $^2P_{1/2}$ States in $^{198}Hg^+$," Wayne M. Itano, J.C. Bergquist, and D.J. Wineland, J. Opt. Soc. Am. B$\underline{2}$, 1392 (1985).

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5. "Angular Momentum of Trapped Atomic Particles," D.J. Wineland, J.J. Bollinger, Wayne M. Itano, and J.D. Prestage, J. Opt. Soc. Am. B$\underline{2}$, 1721 (1985).

6. "Calculated Electrostatic Properties of Ion Traps," E.C. Beaty, Phys. Rev. $\underline{A33}$, 3645 (1986).

7. "Sympathetic Cooling of Trapped Ions: A Laser-Cooled Two-Species Non-neutral Ion Plasma," D.J. Larson, J.C. Bergquist, J.J. Bollinger, Wayne M. Itano, D.J. Wineland, Phys. Rev. Lett. $\underline{57}$, 70 (1986).

BOOKS (AND SECTIONS THEREOF) SUBMITTED FOR PUBLICATION

1. "Lineshape/Linewidth Measurement," by J.C. Bergquist. To be published in Laser Characterization and Control, ed. by J.J. Snyder. (Academic Press).

BOOKS (AND SECTIONS THEREOF) PUBLISHED

1. "Frequency and Time Standards Based on Stored Ions," J. J. Bollinger,
    D. J. Wineland, Wayne M. Itano, J. C. Bergquist, and J. D. Prestage,
    Proc. of the 16th Annual Precise Time and Time Interval (PTTI)
    Applications and Planning Meeting, NASA Goddard Space Flight Center,
    Greenbelt, MD.

2. "Two Photon Optical Spectroscopy of Trapped HgII," J. C. Bergquist,
    D. J. Wineland, W. M. Itano, H. Hemmati, H.-U. Daniel, and G. Leuchs,
    for Laser Spectroscopy VII, ed. by T.W. Hansch and Y.R. Shen,
    (Springer, Berlin, 1985) p. 6.

3. "Doppler-Free Two Photon Laser Spectroscopy of HgII," J.C. Bergquist,
    D.J. Wineland, Wayne M. Itano, H. Hemmati, H.-U. Daniel, and G.
    Leuchs, Proc. 39th Ann. Symp. on Frequency Control, Philidelphia,
    PA, 1985.

PATENTS FILED

None

PATENTS GRANTED

None

INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL
SOCIETY CONFERENCES

1. "Limits for Spatial Anisotropy by Use of Nuclear Spin Polarized $^9Be^+$ Ions", 1985 Gordon Conf. on Atomic Physics; J.D. Prestage.

2. "Trapped Particles" 1986 Spring Forum - Solid State Sciences Committee/Committee on Atomic and Molecular Science, NRC, Washington D.C. March, 1986; D.J. Wineland.

3. "Frequency Standards Based on Stored Ions", Conference on Precision Electromagnetic Measurements," Gaithersburg, MD June '86; D.J. Wineland.

4. "Laser Cooling of a Single HgII Ion." IQEC '86 June '86; R.G. Hulet.

5. "Progress Towards Observation of Quantum Jumps on a Single Ion." DEAP Meeting Eugene, Oregon, June '86; R.G. Hulet.

6. "Liquid and Solid Plasmas", School/Workshop on Laser Cooling and Trapping" Helsinki, July '86; D.J. Wineland.

7. "Single Ion Experiments at NBS", School/Workshop on Laser Cooling and Trapping," Helsinki, July '86; J.C. Bergquist.

8. "Strongly Coupled Ion Plasmas," Strongly Coupled Plasma Physics Meeting, Santa Cruz, CA Aug. '86; L.R. Brewer.

9. "Limits to Accuracy for Stored Ion Spectroscopy," Workshop on Fundamental Measurements on Optically Prepared Atoms," NBS, Gaithersburg, MD, Sept. '86; D.J. Wineland.

OTHER INVITED TALKS

1. "Liquid and Solid Plasmas," Colorado Univ. Colloquium Oct. '85; J.J. Bollinger.

2. "Laser Cooled Trapped Ions," MIT Seminar on Laser Spectroscpy, Nov. '85; D.J. Wineland.

3. "Cooled Ion Spectroscopy," Yale Univ. Seminar, Dec. '85; J.C. Bergquist.

4. "Laser Cooled Trapped Ions," Iowa State Univ. Colloquium, Feb. '86; D.J. Wineland.

5. "Laser Cooled Trapped Ions," Columbia Univ. Hanan Rosenthal Memorial Lecture, Apr. '86; D.J. Wineland.

6. "Strongly Coupled Non-neutral Ion Plasmas," Seminar, Univ. of Calif, San Diego, Apr. '86; J.J. Bollinger.

7. "Laser Cooled Trapped Ions," Univ. of Nebraska, Colloquium Apr. '86; D.J. Wineland.

HONORS / AWARDS / PRIZES

1. Department of Commerce Gold Medal for Cooled Ion Frequency Standard to J.C. Bergquist, J.J. Bollinger, W.M. Itano, and D.J. Wineland, Dec. '85.

2. NBS Condon Award (for written exposition) to D.J. Wineland, Dec. '85.

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Sarah L. Gilbert (NRC post-doc, ONR equipment support)

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